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A review into thermal comfort in buildings

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ABSTRACT

Thermal comfort has been discussed since 1930s. There have been two main approaches to thermal comfort: the steady-state model and the adaptive model. The adaptive model is mainly based on the theory of the human body's adapting to its outdoor and indoor climate. In this paper, besides the steady-state model, three adaptive thermal comfort standards are comprehensively reviewed: the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline. Through a case study from the Netherlands, these standards are compared. The main differences discussed between the standards are the equations for upper and lower limits, reference temperatures, acceptable temperature ranges and databases.

Contents

1. Introduction

One of the more unfortunate aspects of modern global development has been the introduction and widespread acceptance of the use of mechanical means for providing desired comfortable temperature for building users. This phenomenon has led to a huge energy consumption in the building stock, and nowadays, around one third of fossil fuels is consumed in buildings [1]. In this regard, thermal comfort boundaries are limitations which help building physicists to estimate to what extent buildings should be heated or cooled. Thermal comfort is defined as '*that condition of mind which expresses satisfaction with the thermal environment.*'[2]. Prediction of the range of temperatures for this comfort condition is complicated and apart from cultural influences it depends on environmental and personal factors. Chronological review of current knowledge on thermal comfort shows two different approaches: climate chamber tests and field studies. The former, which is based on heat exchange processes of the body, has led to steady-state laboratory thermo-physiological models and standards (ASHRAE 55-1992, ISO7730 and …). The latter has concluded to adaptive thermal comfort models and standards: the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline. Today, these standards are increasingly

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used in research and in practice within the field of thermal comfort. The current paper tries to clarify the differences behind the mentioned standards through a Dutch case study.

This paper first reviews the development of the ideas of thermal comfort, starting with the laboratory studies conducted by Fanger and his co-workers. In the next step, field studies which were done on naturally ventilated (and in a non-steady-state situation) and air conditioned buildings will be explained. Then, three adaptive thermal comfort standards are presented with their equations. In Section 5, a Dutch representative city will be presented as a case study. In this regard, each one of the adaptive thermal comfort standards provides an estimate of the temperature range for thermal comfort. Through the results of the estimations, the standards will be compared and discussed.

2. Development of the concept of human thermal comfort

Research in thermal comfort integrates several sciences such as physiology, building physics, mechanical engineering and psychology. According to Nicol [3], there are three reasons for understanding the importance of thermal comfort:

- To provide a satisfactory condition for people,
- To control energy consumption (elaborated by [4,5],
- To suggest and set standards.

Furthermore, Raw and Oseland [6] suggested six aims for developing knowledge in the field of thermal comfort:

- Control over indoor environment by people,
- Improving indoor air quality (dicussed comprehensively by Khodakarami and Nasrollahi [7–9])
- Achieving energy savings,
- Reducing the harm on the environment by reducing CO_2 production,
- Affecting the work efficiency of the building occupants (discussed by Leyten, Kurvers [10]),
- Reasonable recommendation for improving or changing standards.

Our current knowledge of human thermal comfort is developed by engineers and physiologists. The first concept began by a British physician in 1774. Afterwards, engineers and physiologists developed different indices relating temperature to comfort, and now, building physicists use different thermal comfort standards. Apparently, their endeavours were through two basic methods; steady-state studies and field studies. Most of the steady-state studies were prior to the field studies.

In the past, there have been two general approaches for determining the thermal comfort: (a) climate chamber studies, and (b) field studies:

(a) Climate chamber studies: The aim of these studies is to determine steady-state thermal comfort models. The research is conducted in an environmental test chamber that can vary different climatic parameters. The personal variables (clothing insulation and metabolic rate) are determined by the task, and are normally assumed to be fixed. The most important reason to use such a steady-state situation is the ability to produce the desired environmental conditions (air temperature, radiant temperature, air velocity, humidity) while controlling unwanted variables, which might influence the results. This method has also led to transient body temperature tests which examine body core and skin temperature to estimate comfort perceptions [11].

(b) Field studies: The aim of these studies is to study thermal comfort in the real world. Research is conducted as subjects go about normally with their work; there is no attempt to control the environment that may have varied from just the air temperature to all factors. In many surveys clothing value and metabolic rate are recorded. Furthermore, a field study will be influenced by other indirect factors, such as cultural and psychological factors. The first aim is to discover what combination of environmental variables best describes the subjective responses of the subjects. The underlying assumption of the field survey is that people are able to control their environment in such a way that they try to reach comfort. Therefore, also the behaviour of the building plays an important role [3].

2.1. Steady-state studies

From a physiological point of view, the very early endeavour to understand the regulatory system of the human body temperature dates back to Blagden [12] with his use of a thermometer in a heated room. His experiments were about human ability to endure high temperatures. In 1885, Richet found the ideas of brain regulations in temperature understanding. In the 1930s, Gagge started working on human heat exchange processes [13–16] and he predicted thermal comfort for ASHRAE in 1969 based on a thermal equilibrium approach [17].

In engineering, the first idea of body heat transfer was introduced by Sir Leonard Hill, Barnard [18]. In 1914 he made a big thermometer which integrated the influence of mean radiant temperature, air temperature and air velocity. Furthermore, Dufton [19] defined the equivalent temperature (T_{eq}) in 1929. This equivalent temperature, however, was no longer applied because

Table 1
Chronological development of indices related to thermal comfort (table after [53]).

Year	Index	Reference
1897	Theory of heat transfer	[18]
1905	Wet bulb temperature (T_w)	[23]
1914	Katathermometer	[24]
1923	Effective temperature (ET)	[25]
1929	Equivalent temperature (T_{eq})	[19]
1932	Corrected effective temperature (CET)	[26]
1937	Operative temperature (T_{op})	[15]
1945	Thermal acceptance ratio (TAR)	[27]
1947	Predicted 4-h sweat rate (P4SR)	[28]
1948	Resultant temperature (RT)	[29]
1955	Heat stress index (HSI)	[30]
1957	Wet bulb globe temperature (WBGT)	[31]
1957	Oxford index (WD)	[32]
1957	Discomfort index (DI)	[33]
1958	Thermal strain index (TSI)	[34]
1960	Cumulative discomfort index (CumDI)	[35]
1962	Index of thermal stress (ITS)	[36]
1966	Heat strain index (corrected) (HSI)	[37]
1966	Prediction of heart rate (HR)	[38]
1970	Predicted mean vote (PMV)	[39]
1971	New effective temperature (ET*)	[40]
1971	Wet globe temperature (WGT)	[41]
1971	Humid operative temperature	[42]
1972	Predicted body core temperature	[43]
1972	Skin wettedness	[44]
1973	Standard effective temperature (SET)	[45]
1973	Predicted heart rate	[46]
1986	Predicted mean vote (modified) (PMV*)	[47]
1999	Modified discomfort index (MDI)	[48]
1999	Physiological equivalent temperature (PET)	[49]
2001	Environmental stress index (ESI)	[50]
2001	Universal thermal climate index (UTCI)	[51]
2005	Wet bulb dry temperature (WBDT)	[52]

Table 2
The description of comfort vote units based on ASHRAE, Bedford, HSI (Heat Stress Index= the ratio of demand for sweat evaporation to capacity of evaporation (E_{req}/E_{max}), and zone of thermal comfort classification (Table after [53,54]).

Vote	ASHRAE	Bedford	HSI	Zone of thermal effect
9			80	Incompensable heat
8	Hot (+3)	Much too hot	40–60	
7	Warm (+2)	Too hot	20	Sweat evaporation
6	Slightly warm (+1)	Comfortably warm		Compensable
5	Neutral (0)	Comfortable	0	Vasomotor compensable
4	Slightly cool (−1)	Comfortably cool		Shivering compensable
3	Cool (−2)	Too cool		
2	Cold (−3)	Much too cool		
1				Incompensable cold

Table 3
Recommended operative temperatures for occupants for sedentary activity based on ISO 7730–1984.

Season	Clothing insulation (clo)	Activity level (met)	Optimum operative temp. (°C)	Operative temp. range (°C)
Winter	1.0	1.2	22	20–24
Summer	0.5	1.2	24.5	23–26

environmental variables were not covered in the algorithms [20,21]. In addition, ASHRAE proposed and used the effective temperature, *ET*, from 1919 till 1967 [22]. In 1971, Gagge introduced *ET** which was more accurate than *ET* because it covers simultaneously radiation, convection and evaporation. Table 1 shows the development of indices related thermal comfort.

In parallel, Fanger [39] developed theories of human body heat exchange. Fanger stated that the human body strives towards thermal equilibrium. He proposed the following formula:

$$S = M \pm W \pm R \pm C \pm K - E - RES \quad (1)$$

where

S heat storage
M metabolism
W external work
R heat exchange by radiation
C heat exchange by convection
K heat exchange by conduction
E heat loss by evaporation
RES heat exchange by respiration (from latent heat and sensible heat).

In this system, the thermal responses of subjects are measured by asking their comfort vote for one of the descriptive scales of Table 2:

Table 4
Recommended operative temperatures for occupants with sedentary activity, 50% relative humidity and mean air speed less than 0.15 m/s based on ASHRAE 55-1992.

Season	Typical clothing	Clothing insulation (clo)	Activity level (met)	Optimum operative temp. (°C)	Operative temp. range (°C)
Winter	Heavy slacks, long sleeve shirt and sweater	0.9	1.2	22	20–23.5
Summer	Light slacks, short sleeve shirt	0.5	1.2	24.5	23–26

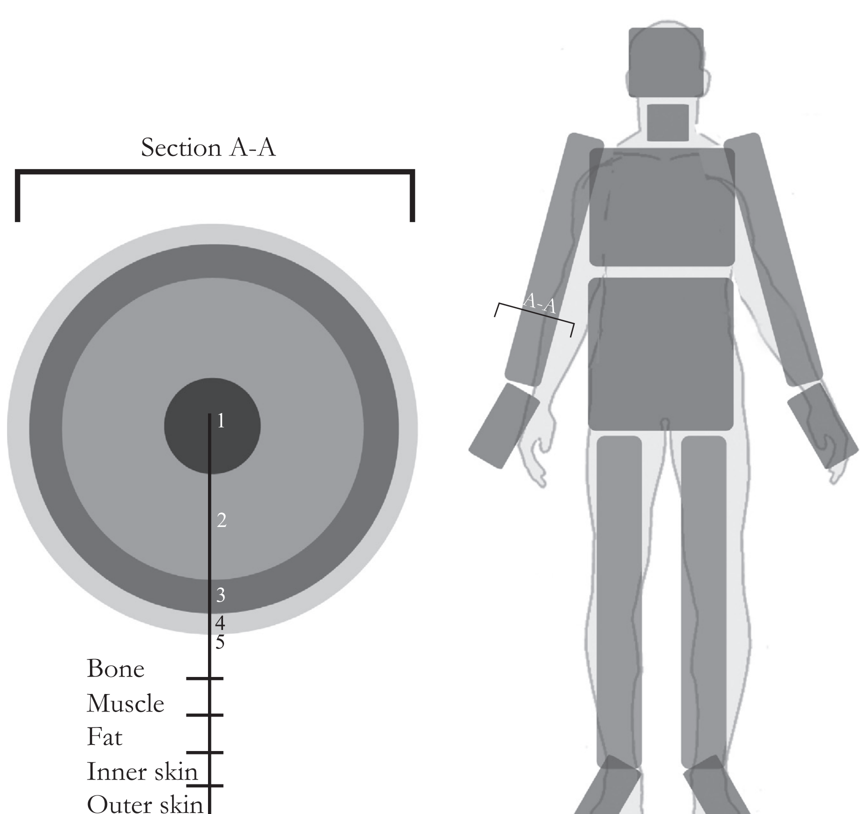

Fig. 1. An example of a schematic diagram of the passive system used in simulations (after [59]).

Furthermore, Fanger introduced six parameters which have an effect of thermal comfort are:

(a) Metabolism refers to all chemical reactions that occur in living organisms. It is also related to the amount of activity. The unit of activity is Watt (W).
(b) The amount of clothing resistance also affects thermal comfort. This parameter is expressed as clo, and it ranges from 0 (for a nude body) to 3 or 4 (for a heavy clothing suitable for polar regions). In this regard, 1 clo = 0.155 °C/W.
(c) An ideal relative humidity between 30% and 70%.
(d) Air velocity has a thermal effect since it can increase heat loss by convection. Moreover, air movement in a cold thermal zone brings draught. The amount of air fluctuations is also important. The unit is normally m/s.

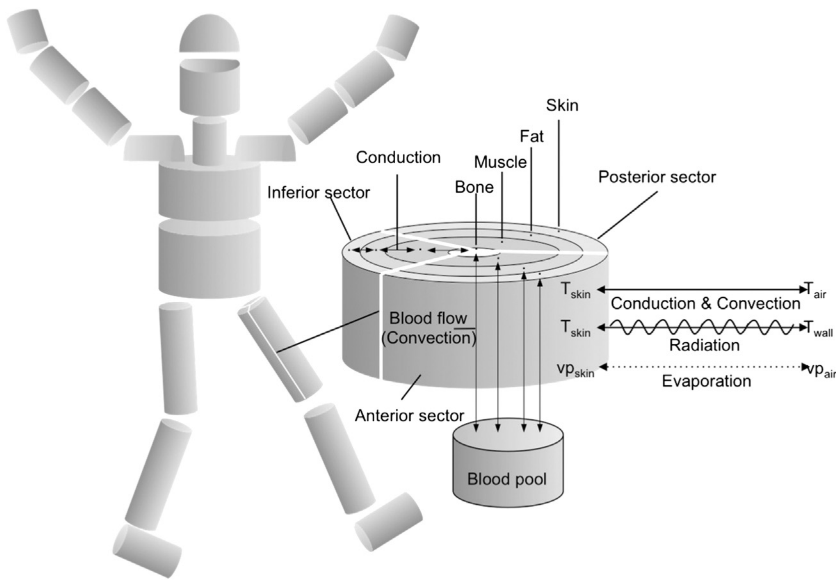

Fig. 2. Schematic view of the ThermoSEM model [68].

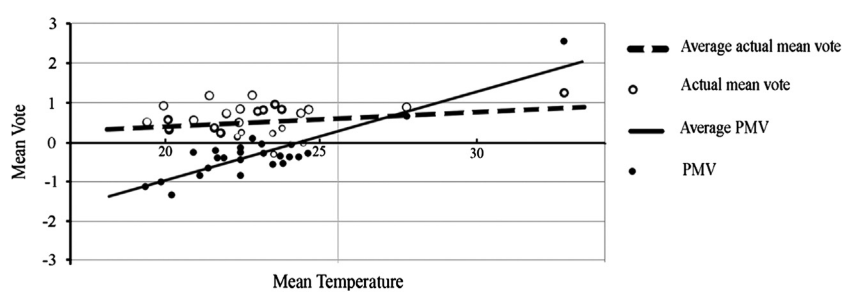

Fig. 3. The difference of comfort predictions between the actual mean vote and the PMV in some field surveys (after [69]).

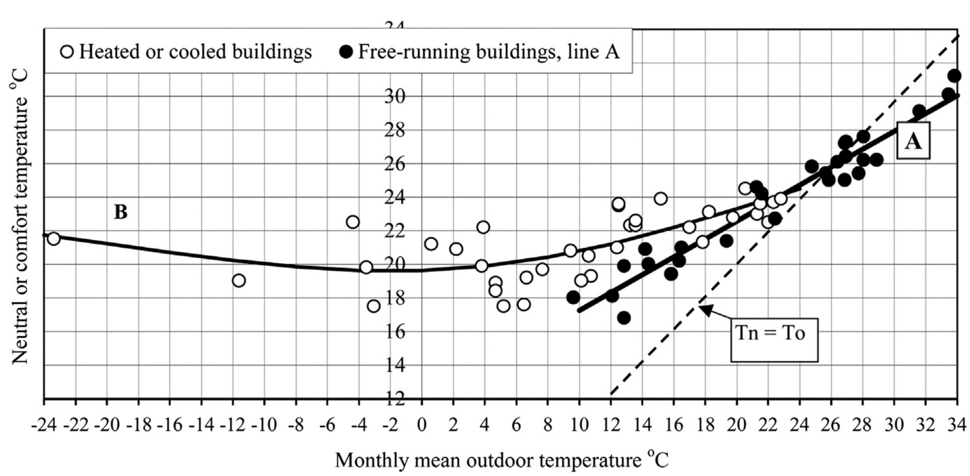

Fig. 4. Comfort temperature vs. outside temperature [75].

(e) The air temperature might be one of the most important ones. This is the temperature of the air surrounding a human body (in Celsius or Fahrenheit).
(f) The other source of heat perception is radiation. Therefore, mean radiant temperature has a great influence for a human body (i.e. how it loses or gains heat from and to the environment).

Later on, Fanger's equation became the basis for ISO 7730-1984 and ASHRAE 55-1992. Tables 3 and 4 show examples of temperature bandwidths that resulted from climate chamber (steady-state) studies.

- Advanced thermo-physiological models

In parallel to Fanger's studies, other advanced thermo-physiological models were introduced. The basis of these studies was the requirements of NASA and the US army [55,56]. "*A thermo-physiological model provides a mathematical description of physiological responses to thermal environments*" [57]. These models, which were developed based on PMV-PPD, could be used to model transient physiological responses (i.e. local skin temperature and body core temperature).

Various studies on thermal stress have concluded to different thermo-physiological models. In these models, the human body is split into several layers. It is considered that the blood circulation system and conduction between the layers cause heat transfer from the body core to the surroundings (Fig. 1). This was possible through the simulation of the human body [58].

Gradually, by increased requirements on the prediction of complex thermal environments (transient and non-uniform), thermo-regulatory models were developed from a single homogenous cylinder into multi-layered cylinders of various sizes, together with thermophysical and physiological properties for individual body parts with applied blood circulation [40,60–67]. In this regard, Fig. 2 shows an example of recent advances with computational fluid dynamics aid to predict the thermal sensation of the human body [57]. In this model, which is called ThermoSEM, the human body is subdivided into 18 cylinders and 1 sphere, all of which also containing layers that represent different tissue materials such as brain, lung viscera, bone, muscle, fat and outer and inner skin [57,68].

2.2. Field studies

By the increase of using Fanger's equation, four main criticisms were announced:

(a) The role of clothing resistance,
(b) Metabolic rate and the activity of subjects,

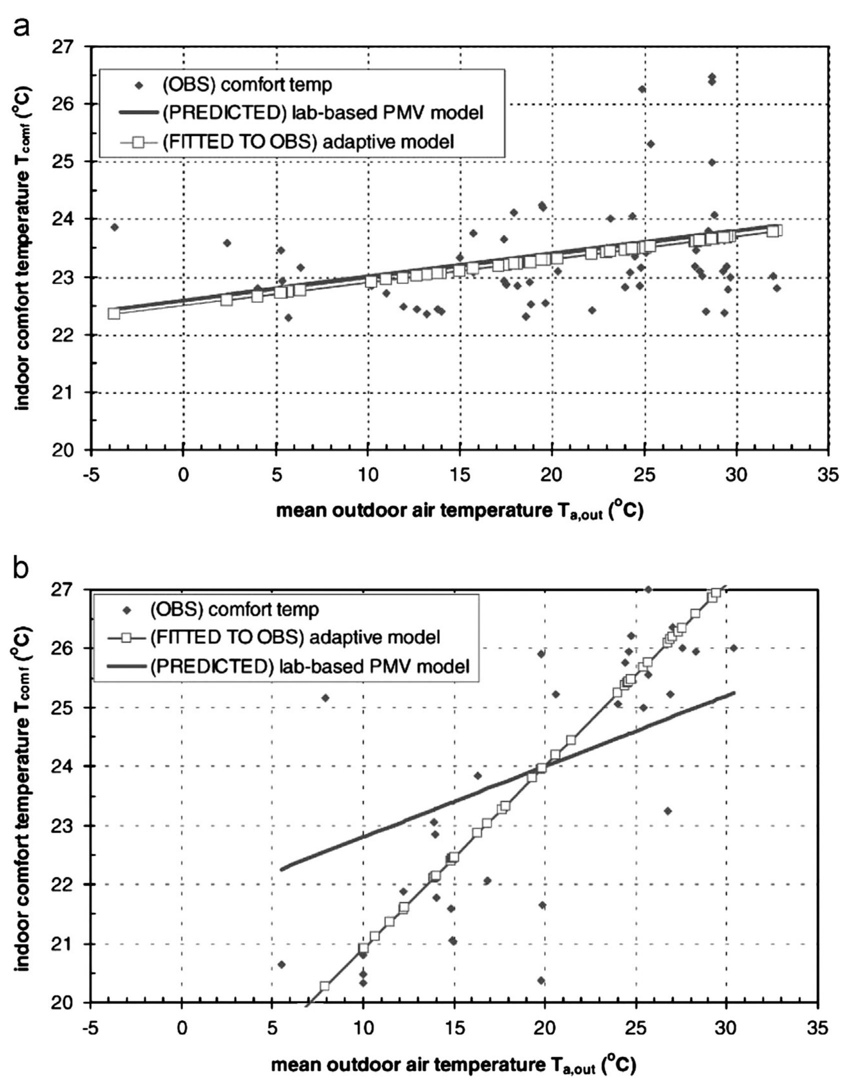

Fig. 5. Observed (BS) and predicted indoor comfort temperature from ASHRAE database for conditioned buildings (top), and naturally ventilated buildings (below) [78].

Table 5
Overview of studies showing differences of comfort temperature between naturally ventilated and conditioned buildings [92].

Reference	Location	Time of year	Subjects	Results
[79]	Brisbane and Melbourne, Australia	Summer	Occupants of air-conditioned and free-running office buildings (n=2242)	Differences in neutral temperatures were 1.7 K and −1.3 K between AC and NV buildings in Brisbane and Melbourne in summer.
[80]	San Francisco Bay Area, USA	Winter and summer 1987	304 subjects (187 females, 117 males) in 10 office buildings (2342 visits)	In winter, the measured neutral temperature (ET*) was 22.0 °C, vs. 24.4 °C predicted by PMV. In summer, the measured neutral temperature (ET*) was 22.6 °C, vs. 25.0 °C predicted by PMV. In both seasons, there was a 2.4 K difference between measurements and predictions.
[81,82]	Bangkok, Thailand	Hot season and wet season 1988	Over 1100 Thai office workers in AC and NV buildings	For both seasons, temperatures at which people expressed optimal comfort had a slightly broader bandwidth in NV office buildings compared to AC buildings. In NV buildings, the PMV model underestimated neutral temperatures by 3.5 K, while in AC building it overestimated by 0.5 K. The upper limits for thermal comfort in both types of office buildings were higher than stated in standards.
[83]	Wuxi, China	All year round	10 students (5 males, 5 females), in residential buildings and a school	People prefer different thermal conditions during long-term exposure without space heating or cooling than based on thermal comfort standards. Local young people accepted operative temperatures of 10–12 °C in winter.
[84]	UK	Winter and summer	Winter: (n=935 questionnaires) +6,050 half-day questionnaires. Summer: (n=5,037 questionnaires), in 4 NV and 4 AC buildings	In NV offices, the neutral temperature was 1.3 to 2.2 K (winter-summer) lower than in AC buildings. At the same time, there were only minor differences between dress code and activity levels. Discrepancies of up to 4 K were found between the observed neutral temperatures in NV buildings and those predicted by the PMV model.
[85]	Ghadames, Libya	Summer 1997–1998	Residents (n=60) of NV (50%) and mechanically (50%) ventilated dwellings	Occupants were comfortable at temperatures to 35.6 °C in traditional buildings compared to 30.0 °C in AC buildings. The PMV model failed to predict comfort temperatures adequately.
[86]	Karachi, Multan, Quetta, Islamabad, Peshawar, and Saidu Sharif, Pakistan	(1) Longitudinal in summer and winter, and (2) transverse with monthly surveys over a year	Both residential and commercial buildings. (n=36 subjects, n=4927 questionnaires). Study 2: (n=846 subjects, n=7,112 data sets)	PMV tended to overestimate the impact of high indoor temperatures especially in summertime conditions, overemphasizing the need for air-conditioning. There was generally little discomfort at indoor globe temperatures between 20 and 30 °C.
[87]	the Netherlands	Summer (≤1990)	Samples from 29 AC buildings, 32 with individual temperature control, of which 21 with natural and 11 mechanical ventilation. Number of subjects not mentioned	Occupants of NV and mechanically ventilated buildings experienced the indoor climate as being warmer than in AC buildings, even though the percentage of dissatisfied (PD) is lower in the first two buildings (PD 25%, AMV 0.5/PD 41%, AMV 1.0) than in air-conditioned buildings (PD 42%, AMV 0.5/PD 49%, AMV 1.0).
[88]	Ilam, Iran	Hot summer and cold winter 1998, and whole year 1999	Occupants of NV buildings. Hot summer (n=513), Cold winter (n=378), whole year (n=30 people, n=3819 questionnaires)	The neutral temperature during the hot summer in the short-term study was 28.4 °C, and 26.7 °C for the long-term study. The neutral temperature during the cold winter in the short-term study was 20.8 °C, and 21.2 °C for the long-term study. People in NV buildings were comfortable at indoor higher temperatures than recommended by standards.
[89]	Samples from Singapore and Indonesia	Rainy and dry seasons (2000–2002)	Singapore (n=538), Indonesia (n=525)	PMV model has discrepancies for NV buildings in the tropics in terms of tolerance and perception of thermal comfort, which is due to lexical uncertainty of the ASHRAE 7-point scale of thermal sensation. People in the tropics may have another perception of the meaning of the word 'warm' than people from temperate maritime climates. In tropical conditions it fails to give accurate information about the temperatures people find comfortable.
[90]	Bari, Italy	Summer (1995, 1999), and winter (1996, 2000)	University students. Sample size: 423 in 1995, 1034 in 1996, 250 in 1999, and 133 in 2000. Building type (two modes): AC in winter, NV in summer	Neutral temperatures were 24.4 °C in summer 1995, 26.3 °C in summer 1999, 20.7 °C in winter 1996, and 20.6 °C in winter 2000. Occupants of NV buildings (summer) regarded a 3.3 K and 2.1 K bandwidth to be acceptable compared to 3.6 K in AC buildings (winter).
[91]	Thailand (Chiang Mai, Bangkok & Mahasarakham, Prachuabkirikhan)	August 2001	Users of AC buildings in private and public sectors (n=1520)	The neutral temperature of people with a post-graduate education level was the lowest around 25.3 °C, while that of the other groups (graduate and scholar) was higher at 26.0 °C. For people

Table 5 (*continued*)

Reference	Location	Time of year	Subjects	Results
				with air-conditioning home, the difference between neutral temperature of every education level is rather small (0.3 K). However, for the other group (no air-conditioning), the difference of 0.9 K is larger. People with higher educational degrees are found to prefer lower indoor temperature compared to the less-educated.

(c) The dynamic character of thermal conditions,
(d) The psychological characteristics of people which can mentally affect the comfort; such as expectation, the ability of acclimatisation and adaptation, etc.

In this regard, Humphreys and Nicol evaluated the validity of comfort theories based on the steady-state endeavours through several field studies [3,69–71]. Briefly, they stated that the range of comfort temperatures in naturally ventilated buildings is much wider than what PMV-PPD models predict (especially in summer). They stated that there is a discrepancy between the findings from field studies and the comfort predictions based on the heat balance model.

Fig. 3 shows that people are comfortable in a wider range of indoor climates than would have been expected from the heat exchange models. When Humphreys [69] calculated the PMV using data from some field studies, he noted that the calculated PMV differs from the actual mean vote and the PMV almost always underestimates the actual mean votes. On the other hand, Fanger [72] suggests that the difference in results arises from “poor data input”. Here, it is essential that all four environmental factors are properly measured and that a careful estimate is made of the activity and clothing. Malama [73] noted that the difference may arise due to the:

1. difficulty of accurately measuring the parameters of Fanger’s equation in the field,
2. difficulty in accounting for short-term fluctuations in those parameters in the field,
3. impact of psychological and cultural factors in the field.

In this regard, based on different studies in several years, Humphreys stated that the application of ISO7730 led to an incorrect evaluation of thermal discomfort because it did not sufficiently reflect a human’s capability of thermal adaptation [69,74–77]. Clearly, with Fig. 4 he showed that indoor thermal comfort is a function of outdoor temperature.

Similar analyses of the ASHRAE databases of comfort surveys showed identical results. deDear and Brager [78] collected field survey results from all around the world and divided them into two categories: naturally ventilated buildings and centrally conditioned buildings. de Dear and Brager showed that the PMV prediction fitted ‘closely’ to conditioned buildings (R^2=53%) (Fig. 5a); however, for naturally ventilated buildings, PMV did not predict accurately (R^2=70%) (Fig. 5b).

These attempts to clarify the differences between naturally ventilated and conditioned buildings continued with later studies which are shown in Table 5.

3. Adaptive thermal comfort standards

The results of Figs. 4 and 5 showed a clear division between people in buildings which were free-running and in buildings that were heated or cooled. The relationship for the free-running buildings was closely linear. However, for heated and cooled buildings the relationship is more complex since the expectations of people in those buildings are different. deDear and Brager discussed the role of expectation explaining the difference between these two building types [93].

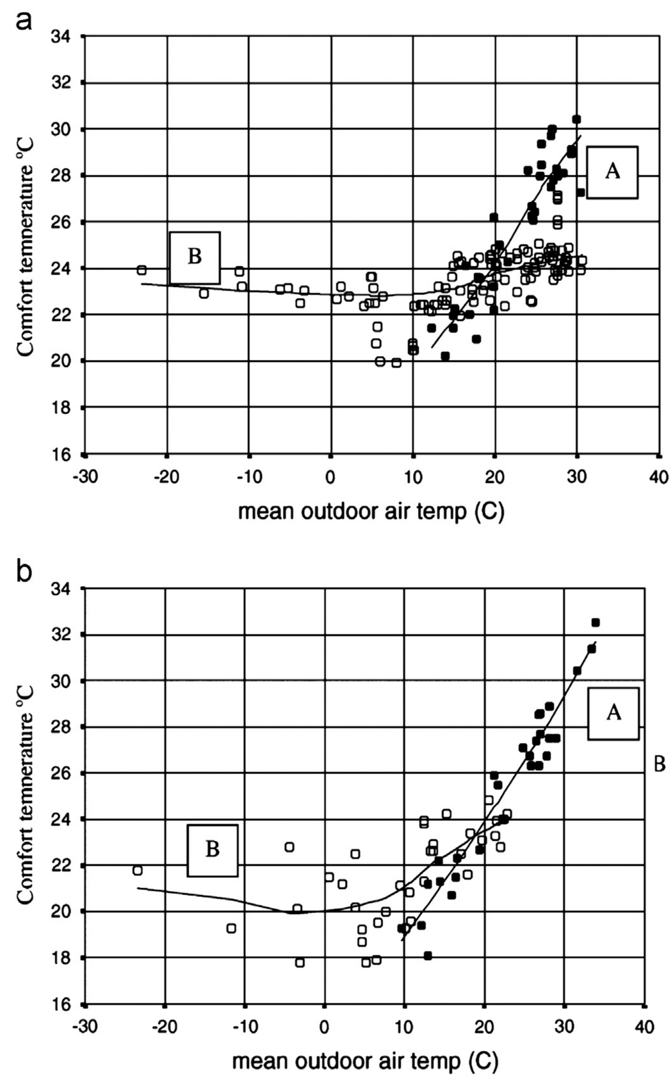

Fig. 6. Comfort temperature as a function of outdoor temperature in free-running buildings (A) and conditioned buildings (B): (top) from the ASHRAE data base from the 1990s [93]; (below) from Humphreys surveys from the 1970s [75].

Fig. 6 shows how the comfort temperatures change with outdoor temperature in buildings which are free-running or conditioned from Humphreys [75] from the 1970s and from the ASHRAE database [94] from the 1990s Fig. 7.

Referring to the linear relationship between comfort temperature and outdoor temperature in naturally ventilated buildings, Humphreys suggested that the desired comfort temperature could

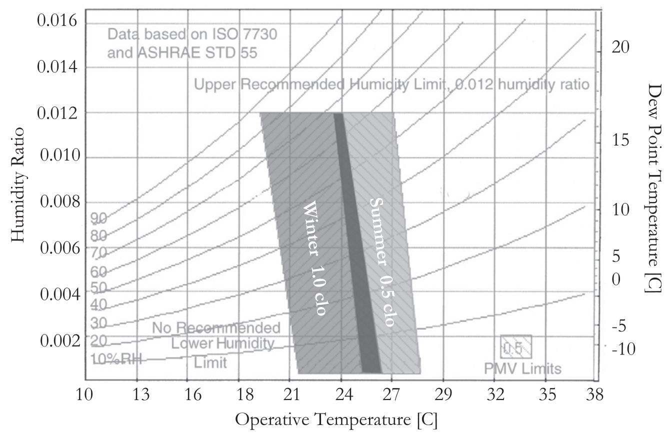

Fig. 7. The Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity for 80% of occupants acceptability (10% of dissatisfied based on PMV-PPD index) for 1.1 met and, 0.5 and 1 clo [97]. 0.5 clo normally refers to summer, and 1 to winter.

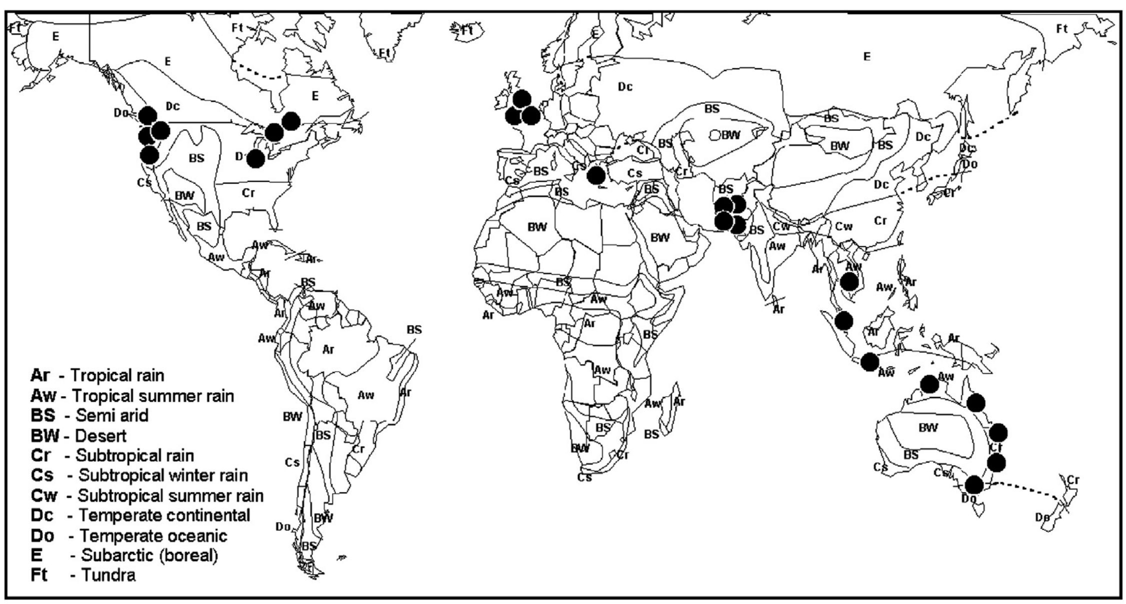

Fig. 8. The geographic distribution of building studies that formed the basis of the adaptive model and adaptive comfort standard of ASHRAE [78].

be determined by a linear equation:

$$T_{CO} = a.T_{out} + b \quad (2)$$

where

T_{co} = comfort temperature (°C),
T_{out} = outdoor temperature (°C),
a, b = constants.

In 1978, Humphreys suggested to use the monthly mean outdoor temperature (T_{rm}) as the outdoor temperature in formula (2). Afterwards, Nicol, Humphreys and McCartney [95,96] showed that an exponentially weighted running mean outdoor temperature gave a more accurate prediction:

$$\theta = (1-\alpha).(\theta_{ed-1} + \alpha.\theta_{ed-2} + \alpha^2.\theta_{ed-3} \cdots) \quad (3)$$

This equation could be simplified to:

$$\theta_{rm} = (1-\alpha).\theta_{ed-1} + \alpha.\theta_{rm-1} \quad (4)$$

where
α is a reference constant value, ranging between 0 and 1,

θ_{rm} running mean temperature of today,
θ_{rm-1} running mean temperature of the previous day,
θ_{ed-1} the daily mean outdoor temperature of the previous day,
θ_{ed-2} the daily mean outdoor temperature of the day before and so on.

In this regard, all these endeavours led to the theory of adaptive comfort. Briefly, this theory states:

If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort [77]. In the next

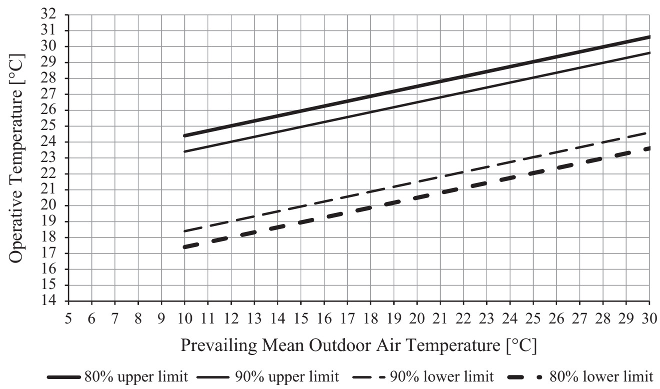

Fig. 9. Comfort bandwidths of ASHRAE 55-2010 [99].

subsections, three basic adaptive thermal comfort standards and guidelines will be described.

3.1. ASHRAE 55-2010

The main purpose of the ASHRAE-55 standard is to specify the combinations of indoor thermal environmental parameters (temperature, thermal radiation, humidity, and air speed) and personal parameters (clothing insulation and metabolism rate) that will produce thermal environmental conditions acceptable to a majority of the occupants. This standard was similar to ISO 7730 in the beginning (which was not adaptive).

In the 1990s, ASHRAE appointed deDear and Brager [98] to conduct a specific research project to collect information from a lot of different field studies performed in several countries: Thailand, Indonesia, Singapore, Pakistan, Greece, UK, USA, Canada and Australia (Fig. 8).

This study showed that occupants' thermal responses in free-running spaces depend largely on the outdoor temperature (and may differ from thermal responses in HVAC buildings). This is due to the different thermal experiences, changes in clothing, availability of control, and shifts in occupant expectations. Therefore, ASHRAE proposed an optional method for determining acceptable thermal conditions in naturally conditioned spaces. These spaces must be equipped with operable windows and have no mechanical cooling system. This method introduces the following equation, which resulted from more than 21,000 measurements taken around the world, primarily in office buildings:

$$T_{CO} = 0,31 \cdot T_{ref} + 17,8\ ^{\circ}C \tag{5}$$

where

T_{ref}= prevailing mean outdoor air temperature (for a time period between last 7 and 30 days before the day in question) [99].

This equation is used for summer when the outdoor temperatures range from 5 °C to 32 °C. In the previous version of ASHRAE 55 (2004), the reference temperature was the mean monthly outdoor air temperature. Fig. 9 shows the comfort bandwidths based on Eq. (5). This figure includes 80% and 90% acceptability ranges of occupants. The 80% acceptability limits are for typical applications and the 90% may be used when a higher standard of thermal comfort is desired. Moreover, the activity level is determined as being less than 1.3 met (normally sedentary activities).

3.2. EN15251

This standard specifies how to establish environmental input parameters for non-industrial buildings (i.e. single family houses, apartment buildings, offices, educational buildings, etc) for design and energy performance calculations [100]. The guidelines of thermal comfort from this standard are based on the Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission. In this project, 26 European buildings in France, Greece, Portugal, Sweden and the UK were surveyed for three years covering free-running, conditioned and mixed-mode buildings [101]. Based on the survey, different adaptive algorithms for each participating country were developed (Table 6).

Table 6
Adaptive comfort algorithms for individual countries [101].

Country	Adaptive control algorithm	
	$T_{rm} \leq 10$ °C	$T_{rm} > 10$ °C
All	22.88 °C	0.302*T_{rm}+19.39
France	0.049*T_{rm}+22.85	0.206*T_{rm}+21.42
Greece	NA	0.205*T_{rm}+21.69
Portugal	0.381*T_{rm}+18.12	0.381*T_{rm}+18.12
Sweden	0.051*T_{rm}+22.83	0.051*T_{rm}+22.83
UK	0.104*T_{rm}+22.85	0.168*T_{rm}+21.63

Based on SCATs project, in 2007 the European Committee for Standardisation (CEN) released EN15251:2007 [100] the following equation for naturally ventilated buildings:

$$T_{CO} = 0.33 \times T_{rm7} + 18.8\ ^{\circ}C \tag{6}$$

where

T_{rm7}= the exponentially weighted running mean of the daily outdoor temperature of the previous seven days based on Eq. (3).

This standard recommends 0.8 for the constant α in Eq. (3) and leads to:

$$T_{rm7} = \frac{(T_{-1} + 0.8T_{-2} + 0.6T_{-3} + 0.5T_{-4} + 0.4T_{-5} + 0.3T_{-6} + 0.2T_{-7})}{3.8} \tag{7}$$

In this standard, the accepted deviation of the indoor operative temperature from the comfort temperature is divided into four categories (Table 7).

Table 7
Suggested applicability for the categories and their associated acceptable temperature ranges (table after [100]).

Category	Explanation	Limit of deviation (°C)	Range of acceptability (%)
I	High level of expectation for very sensitive and fragile users (hospitals, …)	± 2	90
II	Normal expectation for new buildings	± 3	80
III	Moderate expectation (existing buildings)	± 4	65
IV	Values outside the criteria for the above categories (only in a limited period)	$\pm >4$	<65

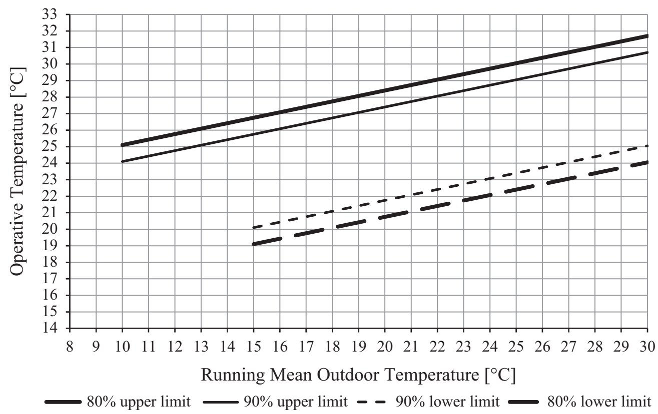

Fig. 10. Comfort bandwidths of EN15251 [100].

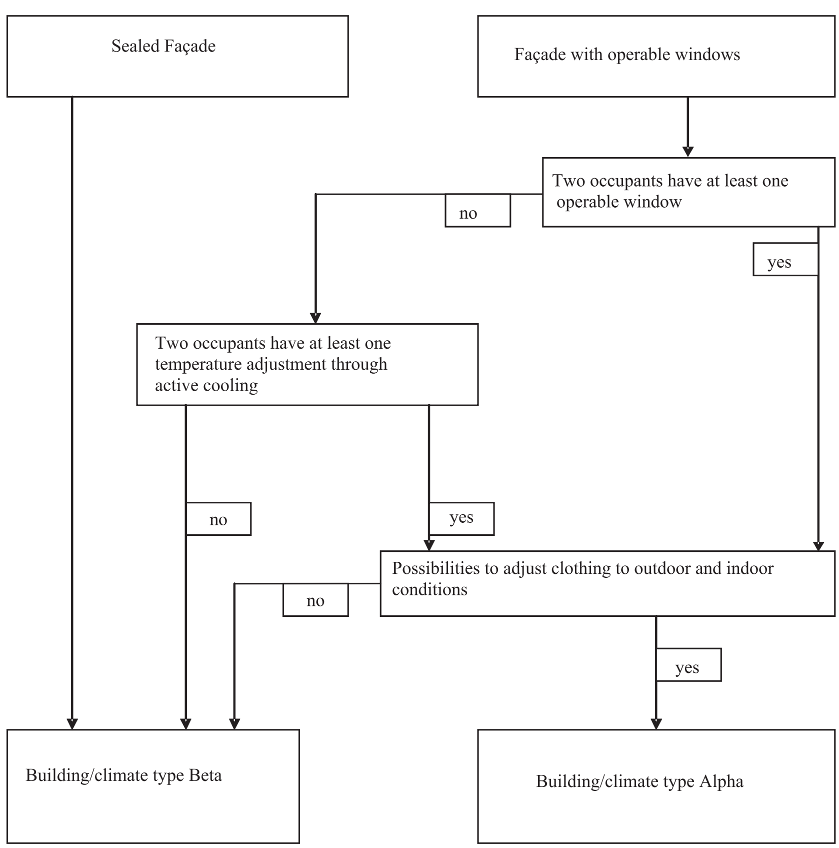

Fig. 11. Diagram for determining the type of building/climate: alpha or beta [103].

Furthermore, based on the comfort algorithm and the range permitted for different percentages of acceptability, Fig. 10 presents the comfort bandwidths.

3.3. ATG

In 2004, the Dutch new guideline for thermal comfort was introduced prior to the European EN15251:2007. This Adaptive Temperature Limits guideline (ATG) was developed as an alternative to the former guideline (in 1970s), the Weighted Temperature Exceeding Hours method (GTO) which was based on Fanger's model [102]. This new standard was established because the former standard did not have the flexibility to predict various types of buildings. In this regard, the new method divides buildings into two types: alpha and beta buildings. The first are naturally ventilated buildings, and the latter mechanically conditioned buildings with sealed facades (Fig. 11).

In Table 8, the equations related to the type alpha are described:

In this case, the outdoor reference temperature is determined by the running mean outdoor temperature, based on Eq. (3) as:

$$T_{\mathrm{rm}} = \frac{T_i + 0.8{\cdot}T_{i-1} + 0.4{\cdot}T_{i-2} + 0.2{\cdot}T_{i-3}}{2.4} \quad (8)$$

where

T_{rm} =running mean outdoor temperature
T_i =average outdoor temperature of the day in question
T_{i-1} average outdoor temperature of one day before (and so on …)

This equation is based on a time interval of 4 days back in time starting from the current one.

Later on, Peeters, deDear [105] developed an adaptive thermal comfort guideline for residential buildings with different activities. They divided a home into three zones: bathroom, bedroom and other rooms (kitchen, study room and living room). In their classification, each zone has its own comfort algorithms since the metabolic rate, clothing and the other variables in human thermal perception are different in each of these zones Fig. 12.

Table 9 summarises the equations based on 80% of acceptability in the different zones:

Table 8
ATG Comfort bandwidths for the alpha type (table after [104]).

Acceptance	Condition (°C)	Algorithm
A-90%	$T_{\mathrm{ref}} > 12$	T_{co}=20.3+0.31$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 12$	T_{co}=22.7+0.11$*T_{\mathrm{ref}}$
B-80%	$T_{\mathrm{ref}} > 11$	T_{co}=21.3+0.31$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 11$	T_{co}=23.45+0.11$*T_{\mathrm{ref}}$
C-65%	$T_{\mathrm{ref}} > 10$	T_{co}=22.0+0.31$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 10$	T_{co}=23.95+0.11$*T_{\mathrm{ref}}$

4. Comparison and discussion

One of the common ways to show the differences between thermal comfort standards is to apply them to estimate comfort

Table 9
Specified comfort temperature bandwidths for dwellings based on [105].

Zone	Condition	Algorithm
Bathroom	$T_{\mathrm{ref}} \geq 11$ °C	T_{co}=20.32+0.306$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 11$ °C	T_{co}=22.65+0.112$*T_{\mathrm{ref}}$
Bedroom	$T_{\mathrm{ref}} \geq 21.8$ °C	T_{co}=26 °C
	12.6 °C≤≤$T_{\mathrm{ref}} < 21.8$ °C	T_{co}=9.18+0.77$*T_{\mathrm{ref}}$
	0 °C≤≤$T_{\mathrm{ref}} < 12.6$ °C	T_{co}=16+0.23$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 0$ °C	Tco=16 °C
Other room	$T_{\mathrm{ref}} \geq 12.5$ °C	T_{co}=16.63+0.36$*T_{\mathrm{ref}}$
	$T_{\mathrm{ref}} < 12.5$ °C	T_{co}=20.4+0.06$*T_{\mathrm{ref}}$

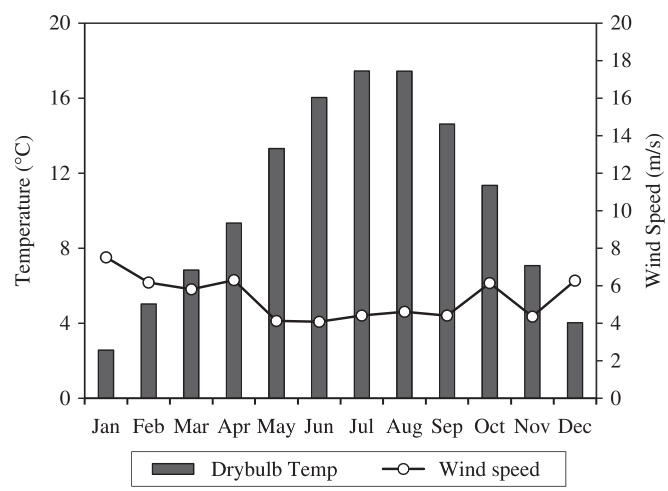

Fig. 13. Representative mean dry bulb outdoor temperature and mean wind speed of De Bilt.

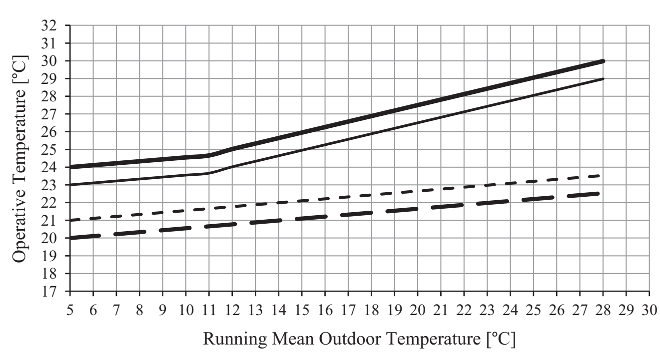

Fig. 12. Adaptive comfort bandwidths (for naturally ventilated buildings) according to ATG [103].

Table 10
Representative weather data of De Bilt as used in the calculations.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	2003	2004	1992	2002	1986	2000	2002	2000	1992	2004	2001	2003

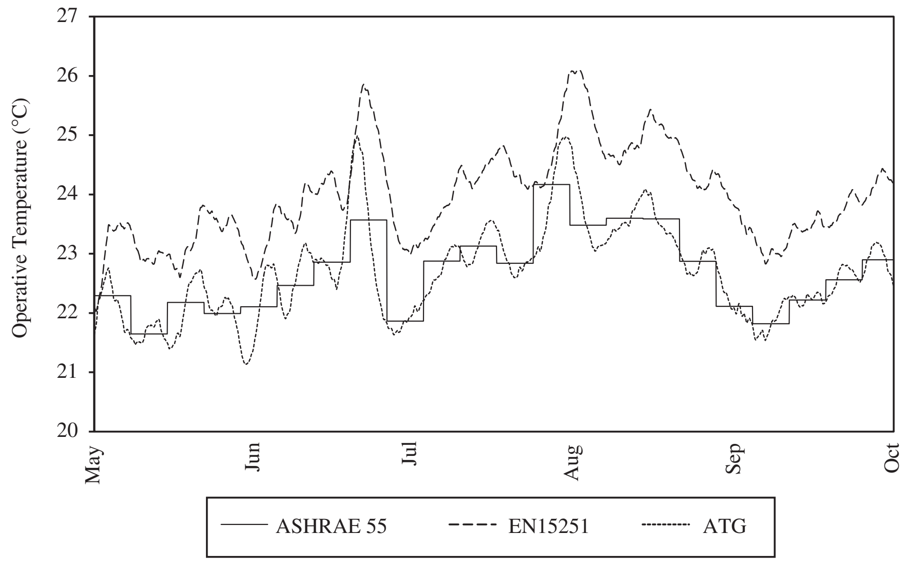

Fig. 14. Indoor operative thermal comfort temperature estimated by the standards for De Bilt.

Table 11
Comparison of the comfort standards for summer time.

Standard	Database	Applicability	Range of acceptance (°C)	Reference temp	Equation
ASHRAE 55–2010	21,000 measurements taken primarily in office buildings	Office buildings	±3.5	Prevailing mean outdoor air temperature	17.8 °C $+0.31\times T_{\mathrm{ref}}$
EN15251	SCATs Project; office buildings	Offices; comparable buildings with sedentary activities	±3	$T_{rm7}=(T_{-1}+0.8T_{-2}+0.6T_{-3}+0.5T_{-4}+0.4T_{-5}+0.3T_{-6}+0.2T_{-7})/3.8$	18.8 °C $+0.33\times T_{rm7}$
ATG	ASHRAE55-2004;GTO Guideline	Office spaces and comparable spaces	±3.5	$T_{rm4}=(T0+0.8T_{-2}+0.4T_{-3}+0.2T_{-4})/2.4$	17.8 °C $+0.31\times T_{rm4}$

temperatures of a city or climate [106–112]. In this section, the mentioned American, European and Dutch standards are used to estimate the indoor comfort temperature of the town of De Bilt in the Netherlands. The climate of De Bilt (52°N, 4°E), representing the climate of the Netherlands, is known as a temperate climate based on the climatic classification of Köppen-Geiger [113]. The prevailing wind is South-West. The mean annual dry bulb temperature is 10.5 °C (Fig. 13). In this paper, the reference weather data of De Bilt is used according to Dutch standard NEN5060. According to this standard, every month belongs to a specific year which is representative of the period of 1986 till 2005. The selection is presented in Table 10.

Furthermore, based on the comfort algorithm and the range permitted for 80% of acceptability, Fig. 14 presents the indoor operative comfort temperatures during the free running mode period in De Bilt. The duration of this period is based on the former Dutch energy performance standard for residential buildings [114]. This standard states that the free running mode typically occurs from 1st of May till 30th of September in the Netherlands. Table 11.

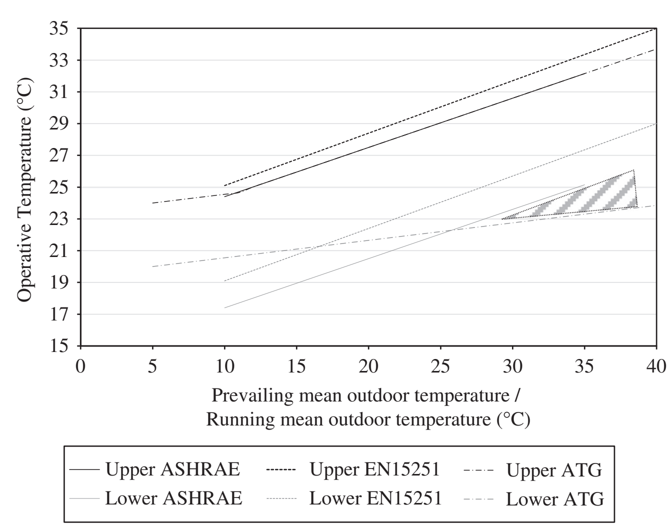

Fig. 15. The upper and lower limits of the thermal comfort standards for 80% of acceptability.

Based on the different estimations for the period of 5 months, the average comfort temperature of ASHRAE is 22.7 °C, EN15251 is 24.0 °C and for ATG is 22.7 °C. Moreover, Fig. 14 depicts clearly that the comfort temperatures have rhythmic differences. The differences are mainly due to:

(a) The intercepts are different (Fig. 15). As an illustration, ASHRAE has the lowest estimated comfort temperatures because its intercept is the lowest (17.8 °C referring Eq. 5).
(b) Calculation of the reference temperatures is different in the standards. ASHRAE 55 in its 2004 edition uses monthly outdoor dry bulb temperature. This wide period of time reduces the accuracy of the reference temperature because there might be lots of fluctuations in the weather. Therefore, this period is allowed to be limited from 30 days to at least 7 days in ASHRAE 55-2010 edition. EN15251 uses the exponentially weighted running mean of the daily outdoor temperature of 7 days before the day in question.
(c) The lower bandwidths have different slopes. The slopes in the upper limit are more or less identical (0.31 for both ASHRAE and ATG, and 0.33 for EN15251). However; the Dutch standard uses a slope of only 0.11 for the lower limit. This is shown with a grey hatched triangle in Fig. 15.
(d) The acceptable variations from the optimum temperature (most comfortable temperature) are different. ASHRAE and ATG allow ± 3.5 °C and EN15251 uses ± 3 °C. This 1 °C difference (in total upper and lower limit) can cause differences in calculations.
(e) Last but not least, the databases of field studies led to the equations of the standards are different in location and size. ASHRAE used 21,000 measurements from many countries (excluding countries in Africa and South America). The European standard has tried to use data from different climates in Europe (such as France, Sweden, Portugal, Greece and the UK). Finally, ATG used a Dutch database from 2004.

5. Conclusions

This paper reviewed the development of the idea of human thermal comfort. Steady-state and field studies were described chronologically. As the main result of the field studies, three internationally well-known thermal comfort standards: ASHRAE 55-2010, EN15251:2007 and ATG were comprehensively presented. In each standard, database, basic equations, upper and lower boundaries and reference temperatures were discussed comprehensively. In this paper, the standards were elaborated in a way to be applicable for naturally ventilated buildings. Through a case study from the Netherlands, the standards were compared. The results obtained from the estimation of thermal comfort for the city of De Bilt showed excellent agreement with the corresponding literature reviewed. The main differences between the standards were related to the equations for the upper and lower limits, reference temperatures, acceptable temperature ranges and databases.

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